State-of-the-art and Development Needs of Simulation Codes for Offshore Wind Turbines

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***Abstract**: Offshore wind turbines have been installed in increasing water depths over the last years. Support structures with monopile or gravity based foundation could successfully be used for all realized offshore-projects, but the trend of increasing water depths reached a level that makes application of those relatively simple types of support structures inappropriate. New concepts like tripods or lattice types are developed covering all parts of the support structure.*
A number of sophisticated codes exists that can simulate offshore wind turbines in an integrated and/or superimposed manner, but most of them are currently limited to tubular towers with monopile or gravity based foundations. Therefore those codes are extended to meet the requirements of modelling more complex support structures such as tripods, jackets and even floating structures.
This paper gives an overview on certain aspects related to offshore wind turbine modelling focusing on the support structure and the offshore environment. In this context the current status of a number of simulation codes is presented. Needs and current development related to support structure concepts, system and sub-system models will be discussed taking into account the requirements within the design process as well as limitations of some models. Furthermore, some recent and future verification activities are discussed.

1. Introduction

Since installation of the first offshore wind farm in 1991 more than 330 offshore and near-shore wind turbines have been erected. Almost all projects have been realized with mono-towers on monopile or gravity based foundations. So far, water depths up to 18 m and a maximum distance to the shore of 20 km could be exploited. A survey of existing and planned projects shows a tendency of increasing water depths, distances to the shore and power of the single turbines and wind farms.
Hydrodynamic and indirectly also aerodynamic loads on the support structure increase with water depths, therefore well established support structure concepts of the first generation such as mono-towers with monopile foundations become inadequate from a certain range of water levels on. Alternative concepts e.g. of tripods or jacket types with piled foundations, gravity based foundations or suction caissons, are currently developed to meet the requirements of deeper water sites. While the established types of support structures, sufficient for water depths up to approx. 25 m, may be regarded as relative simple all currently investigated alternative concepts shows an increasing degree of complexity. Even structures of the floating type are in todays discussion, but it seems that a second generation of support structures, adequate for water depths up to approx. 40 m, will still be bottom-mounted nonetheless due to economic reasons. A third generation of offshore wind turbine (OWT) support structures may already be of the floating type, suited for even deeper water.

OWT shows a high degree of dynamic behaviour caused by environmental loads interacting with the structure. Furthermore, interactions of different parts of the OWT leads to the requirement of sophisticated and specialized models for design calculations and simulation of loads and performance in the detailed design phase. The use of simplified models, neglecting a certain amount of interactions, may be appropriate in the early design stages, but will result in both underpredictions or overpredictions of loads and other quantities. Therefore, calculation and optimisation of OWT requires application of sophisticated simulation codes.

This paper gives an overview on certain aspects related to offshore wind turbine modelling focusing on the support structure and the offshore environment in the second chapter. In this context the current status of a number of simulation codes is presented in the third chapter. Chapter four deals with development needs for both, the design process as well as scientific research. Furthermore, current developments as well as some recent and future verification activities are discussed.

2. Offshore Wind Turbine Modelling

OWT are subject to environmental influences transferred from the surrounding air, water and soil causing loads which interacts with the OWT as well as with each other as shown in Figure 1. On the other hand the OWT may significantly influence the environment. Loads and interactions are divided into three fields: aero-elastics, hydro-dynamics and soil-structure interactions. Most of the simulation codes presented later in this paper are capable of calculating loads from the wind and water environment, while soil-structure interactions are only considered in a very crude way derived from results of additional geotechnical tools.

During the design process different kind of models may be desired dependent on the actual design task and phase. More details on that are presented in Section 4.1. Models for the analysis of OWT may be divided and characterized with respect to different aspects. One aspect certainly is the degree of detailedness and the consideration of interactions between the different parts of the OWT.
Integrated system models deal with the OWT as a whole unit together with the air, water and soil, considering occurring interactions within the OWT and with the environment as complete as possible and practical. Therefore, aero-elastics, dynamics of the electrical and control system, structural dynamics of the rotor, drive train and support structure together with their simultaneous response under combined aerodynamic, hydrodynamic, electrical loads as well as their mutual interactions are treated within such models as indicated by Figure 1. Obviously, integrated system models shows a high degree of complexity and, therefore, requires adequate simulation tools.

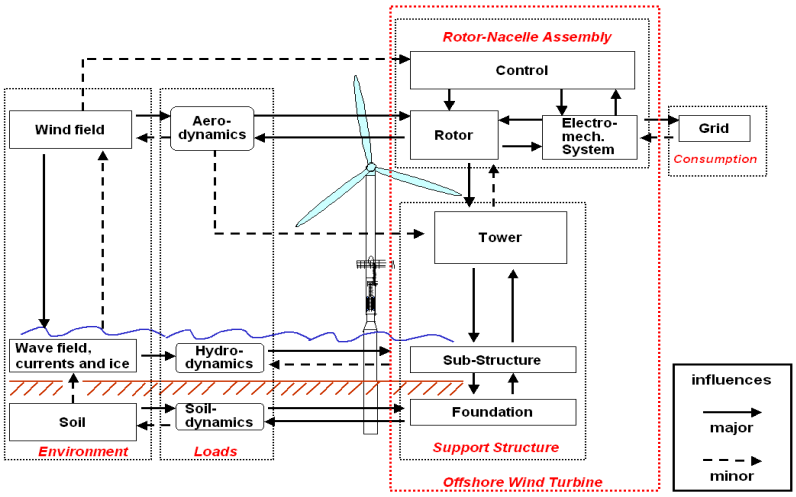

Figure 1: Environmental influences, structural components and interactions within an integrated system model

Sub-system models on the other hand consist of a group of components, e.g. support structure or the rotor-nacelle assembly (RNA). Those components are modelled relatively detailed considering the relevant interactions, while the remaining parts are modelled in a crude manner e.g. applying loads directly at the interface to other sub-systems without interactions. For example consider a support structure model with a lumped top mass and damping element representing the RNA.
Component models deal with single parts such as piles, blades or tubular joints. Calculations of single parts are required for dimensioning, the optimisation and evaluation of representative properties for more complex, but less detailed models as well as for certification.

The underlying models of the whole OWT, sub-systems, components or environmental influences for design calculations shows different requirements compared to models for scientific purposes. Obviously, the different kinds of models serve different objectives. While scientific or research calculations in many cases buy a high degree of accuracy with high costs in cpu-effort, industrial calculations need fast computation for economic design optimisation. Therefore, time-consuming models for design iterations are impractical and simpler models and methods are used, e.g. blade element momentum theory instead of computational fluid dynamics for aerodynamic design calculations and simple spring(-damper) models instead of detailed models using FEM for pile-soil interactions.

2.1. Support structure concepts

Main tasks of the support structure comprise the transfer of loads into the soil, i.e. into sea bed, as well as keeping the rotor-nacelle assembly on the designed hub height and supporting it with a certain dynamic stiffness. The support structures of OWT consist of the whole structure below the yaw system. However, a more detailed separation of the support structure in distinct parts or modules for the purpose of modelling and disposion into different concepts is convenient. In this context the offshore support structure is divided in the tower, the sub-structure and the foundation as suggested by IEC [1] and GL [2] as shown in Figure 2.
Different concepts exist for these three parts of the OWT. Figure 3 presents an overview of common types representing the first and second generation of bottom-mounted concepts. The difference

between monopiles and piles in the figure is given by the type of loading. Monopiles are mainly laterally loaded while piles experience significant additional axial loads.

It should be mentioned that other concepts or slight modifications of the given concepts, e.g. guyed mono-towers or lattice structures as used onshore for the tower, may also become relevant.

Combinations of those support structure modules result in a large variety of support structure concepts, which show different requirements on the underlying structural models. Furthermore, more differentiated denotations are needed for today's variety of concepts than in the common linguistic usage since such denotations of most of the support structure concepts are ambiguous and actually refer to only the sub-structure and/or foundation. A jacket for example may be founded on piles, suction caissons or even on a gravity base. Therefore, if necessary for non-ambiguous definitions, the support structures will consequently be denoted by their tower as well as foundation concepts, e.g. piled jackets, suction caisson founded tripods, etc. Using this classification of support structure components additional clarification is needed. Especially, foundations of the monopile and gravity base type commonly also include the sub-structure or parts of it.

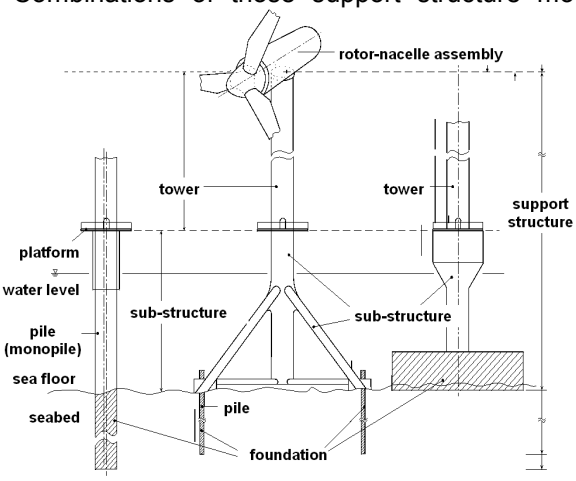

Figure 2: Parts and denotations of the support structure according; modified figure from IEC [1]

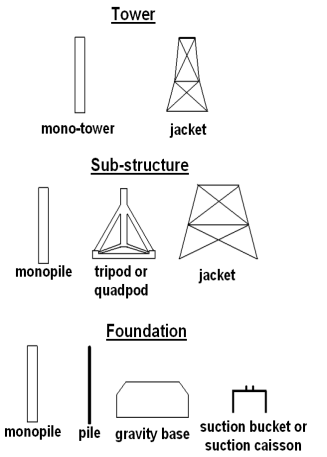

Figure 3: Tower, sub-structure and foundations concepts for bottom-mounted OWT

Tower and sub-structure

A variety of tower and sub-structure combinations is possible using the aforementioned concepts. Table 1 presents an overview of the most probable combinations. Modelling, description and optimisation of mono-towers and monopiles within simulation codes can be handled relatively easily. Braced sub-structure concepts from the second generation of bottom-mounted OWT on the other hand show a significant increase of the number of design parameters. A qualitative estimation of the number of design parameters for the different sub-structure concepts is presented in Figure 4. For convenience, relatively simple configurations with constant cross-sections of the single members are assumed.

Table 1 Combinations of tower and sub-structure concepts

		Sub-structure		
		monopile	tri-, quadpod	jacket
Tower	mono-tower	×	×	×
	lattice tower			(×)
	jacket			×

Since the sub-structures are assumed to be rotationally symmetric, corresponding members show the same cross-sections as well as the same node distances r_i from the centrelines. Accordingly, in the given configurations, the number of design parameters, i.e. cross-sections (diameter D_i and wall thickness t_i) and coordinates (height level z_i and distance from centreline r_i) of the tubular members is equal for tripods and quadpods as well as for different base layouts of the jacket (triangular or square). Clearly, a more detailed approach takes into account more design parameters due to different materials, non-constant cross-sections, joint behaviour, etc. However, even this simplified estimation of the number of design parameters indicates that approx. twice the number of design parameters must be considered for tripods compared to monopiles and even 3-4 times more design parameters will have to be taken into account when dealing with jackets compared to tripods. Therefore, a more differentiated approach within the design process is required for complex structures supported by adequate tools, e.g. provided with a graphical user interface, design plots, generic towers and sub-structures, etc. Only a sophisticated design methodology will facilitate the design of economically viable OWT of the second generation and counterbalance the current lack of experience with such structures. More details on the design process are presented in section 4.1.

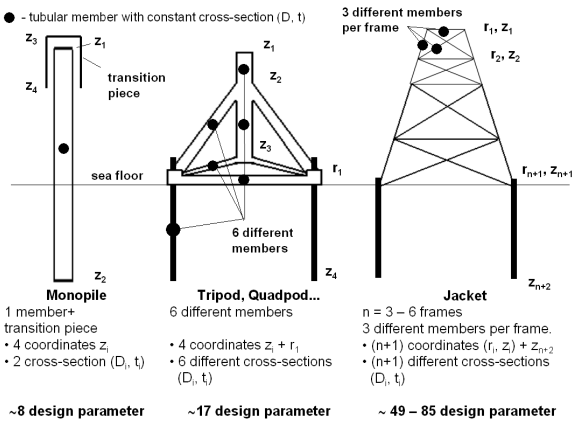

Figure 4: Number of design parameters for different sub-structure concepts on piled foundations

Foundation

Loads are transferred into the seabed by the foundation. Different mechanisms and effects are associated with different foundation concepts. In most of today's simulation codes, representations and modelling capabilities of the foundation are very crude. Using a typical onshore-representation of the foundation by two uncoupled (rotational and translational) springs, possibly combined with an apparent fixity length approach, is still common practice in many codes. Gravity-based foundations may be treated adequately with this method, but important information is lost for piled foundations, which may be regarded as the most important foundation type for both current and near-future bottom-mounted OWT. This combined approach allows for fitting of the first two support structures (fore-aft and lateral) eigenfrequencies and eigenmodes as well as loads above sea floor with good accuracy. However, it is clearly inadequate for the design of piles because ultimate loads as well as fatigue loads will be under-predicted as the maximum bending moment within the piles will occur below sea floor. Due to the more emphasized axial load transfer of braced structures with pile foundations this under-prediction of loads is more critical for monopile founded structures, i.e. for mainly laterally loaded piles. Therefore, a minimum approach for the design of piled foundations should involve linearized, uncoupled (Winkler-type) springs distributed over the length of the sub-soil part of the pile. Typical models for piled foundations are presented in Figure 5. Suction caissons will be used in a way similar to piles, either one compact monopod caisson or multiple caissons for brace structures. Load transfer mechanisms and therefore modelling of such caissons on the other hand significantly differs from piles.

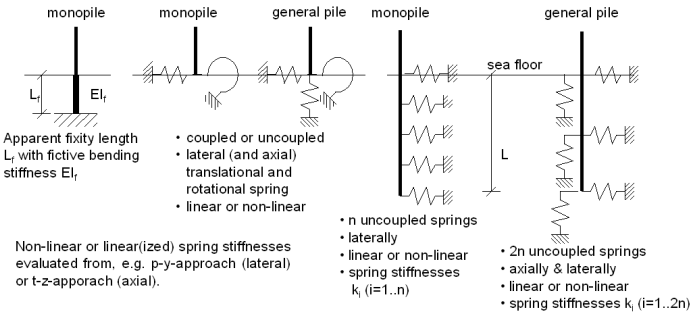

Figure 5: Typical models piled foundations

A significant increase in cpu-time for simulation may be expected when taking the non-linear soil properties into account. The relevance of this non-linearity should be investigated in the final design stage and for certification. Almost none of the current state-of-the-art simulation codes is capable of evaluating foundation properties, i.e. foundation stiffness, on the basis of given soil properties, e.g. by using the p-y method. Another major problem is the current lack of adequate models for the soil response of cyclic loaded piles with large diameters. Although detailed FE-models for this problem are currently under development, e.g. [3] as shown in Figure 6, it is obvious that such detailed models are hardly compatible with the needs of the design process.

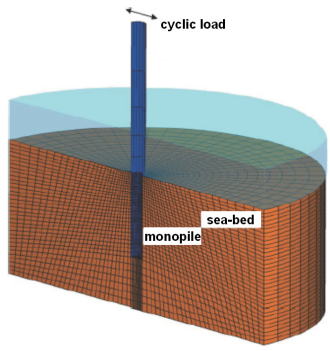

Figure 6: FE-model for the pile-soil interaction due to cyclic loading; figure from [3]

2.2. Rotor-nacelle assembly

According to Figure 1, the RNA is defined as everything carried by the support structure, comprising all physical parts such as the drive train and the generator as well as non-physical parts such as the control algorithms. A detailed sub-system model of the RNA requires application of mechanical, electrotechnical, structural and aeronautical engineering. However, extensive knowledge regarding RNA exists from onshore wind turbines which can relative easily be adapted to OWT. Variations from configurations of onshore wind turbines mainly comprise installations and design details, such as isolations and stationary cranes that affect the structural model and dynamic behaviour only to a minor content. More modifications in the RNA of future OWT can be expected due to increasing power and sophisticated control. Therefore, continuous development of RNA modelling takes place and is absolutely required for both onshore and offshore applications. The challenge of modelling the RNA of OWT lies in the complexity of the aero-elastic behaviour of these extremely large machines rather than in structural differences between onshore and offshore design. Using a typical onshore model for the RNA is common practice when designing and simulating OWT. As this paper focuses on the offshore specific aspect the reader is referred to the literature (e.g. to reference [13]) for more details.

2.3. Environmental conditions and loads on the OWT

OWT experience significant influences in various ways by site-specific environmental conditions such as wind, waves, sea currents, water level variations, sea ice, marine growth and scour . On one hand the environment causes loads on the structure resulting in a dynamic or quasi-static response. On the other hand, environmental conditions and loads have an impact on the dynamic and static properties of the structure.

Waves, currents and hydrodynamics

Hydrodynamic loads on the OWT mainly arise from waves and currents, but other sources e.g. from ice drift may also occur. Wave loads, as the most important source of hydrodynamic loading, can occur due to wave passage, wave breaking as well as due to wave slam and slap. Classification of waves is possible with respect to various characteristics such as source of wave generation, wave description (deterministic or stochastic), wave form (linear or non-linear description), deep water or shallow water waves, etc. The most important types of wave loads relate to wind-induced waves. Although the correlation of the wind and wave fields for such types of waves is obvious, a formulation is not straightforward and depends on many other parameters and on the site conditions.

Descriptions of the wave field are possible by deterministic and stochastic approaches. Commonly, deterministic approaches are preferred for extreme load calculations, while stochastic approaches are preferred for fatigue loads[1]. In both cases wind and wave loads act simultaneously within the integrated models of the state-of-the-art simulation codes. As shown by Kühn [5], this combined wind and wave loading leads to reduced loads compared to superimposed loads from isolated calculations.

Calculation of the wave field addresses to wave kinematics from which the single types of wave loads are derived by different methods. Many wave theories are available for the evaluation of wave kinematics. Single waves may be treated with linear or non-linear wave theories. If waves show a small elevation compared to the water depth, non-linear terms in the solution of the potential equation are neglectable and the wave can be considered linear (Airy wave). In other cases non-linear wave theories are required. Both linear as well as non-linear waves occur on relevant sites for OWT of the first and second generation. OWT on floating structures on the other hand will probably be installed on deep water sites with mainly linear waves.
Sea states are typically represented by wave energy spectra. Different types of spectra are used, e.g. Pierson-Moskowitz and JONSWAP spectra. In the most common approach the sea state is assumed to be adequately represented by a superposition of linear waves with random phase angles. Based on the work of Sobey [14], Mittendorf [15] showed that more accuracy is achieved when using the superposition of linear waves for the approximation of the water surface combined with the method of local Fourier approximation for evaluation of the wave kinematics.

For wave loads on slender (hydrodynamic transparent) structures like monopiles and braced structures the Morison equation is most commonly used. The basic Morison equation uses two semi-empirical coefficients and allows for calculation of drag and inertia forces on the structure. Furthermore, by taking the relative motion of the structure into account, calculation of water-added mass is also possible. Compact structures like gravity base foundations and floating structures significantly influence the wave field and the basic Morison equation becomes inappropriate. Either diffraction theory based on a potential flow theory or a correction of the Morison equation e.g. according to MacCamy-Fuchs [19] should be applied instead. In addition, two other methods for wave load calculation should be mentioned Froude-Krylov (or pressure integration) and CFD (computational fluid dynamics). However, both are currently of minor relevance for wave load calculation of bottom-mounted OWT. Table 2 as presented by Henderson, Zajier and Camp [20] gives an overview on the specific capabilities of the single methods.

Table 2 Capabilities of different wave load calculation methods [20]

			Morison		Diffraction	Froude-Krylov	CFD
Time / Frequency Domain			TD	FD	FD	TD	TD
Forces	Transverse	inertia	√	√	√	√	√
		drag	√	√ [5]	X	X	√
	Lateral (drag)		√	√ [5]	X	X	√
	Pressure		X [1]	X [1]	√	√	√
Geometry	Diffraction		X [2]	X [2]	√	X [3]	√
	Surface Effects [6]	1D	√	√	X	√	√
		3D	X	X	X	√	√
	Massive Structures		X	X	√	√	√
Wave Model	Non-linear & extrapol. waves		√	X	X	√	√
	Stochastic (Linear)		√	√	√	X [4]	X [4]
Applicability (* = poor / *** = good)	Commercial Availability		***	***	***	**	*
	Ease of Use		***	**	**	**	*
	Calculation Speed		**	***	***	*	*

[1] = can be modelled relatively easy by adding an extra term
[2] = can be modelled using MacCamy-Fuchs [19] correction for simple shapes
[3] = must be estimated
[4] = high demands on computation power
[5] =linearized
[6] = non-linear surface effects between the structure and the wave field
1D = in vertical direction only (wave height considered only at the vertical axis of the structure
3D = full geometric field (i.e. wave height at each surface element of the structure)

When the wave steepness exceeds a certain limit the wave will break. Breaking waves are divided into three types: plunging breaker, spilling breaker and surging breaker. Support structures subject to breaking waves

[1] Deterministic concepts also exist e.g. by API [4] and are widely used for many offshore structures in the oil & gas industry. The dynamic characteristics and the general importance of fatigue for OWT require, however, stochastic concepts.

experience additional impact loads. Since the basic Morison equation is inadequate for such impact loads, improvements are required e.g. according to Wienke [6]. This impact load model for slender, cylindrical structures defines an additional term in the basic Morrison equation and is suggested by IEC [1] and GL [2]. Alternatively, Boussinesq based wave models [7] may be applied to derive the conditions caused by breaking waves. Furthermore, such a model allows for calculation of wave transformation due to the bottom slope. Peeringa [8] showed that an asymmetry of the waves caused by the slope of the sea bed, in relation to water depth and wave steepness, may also have a significant influence on wave loads.

Wind field and aero-elastics

Interactions of the rotor with the wind field resulting in loads on the rotor and changes in the wind field are denoted as aerodynamics. Aero-elastics describes the interaction between aerodynamics and structural dynamics of the blade and entire wind turbine system. All state-of-the-art simulation codes allows for aero-elastic calculations, which is required by the design standards IEC [1] and GL [2]. Calculation of the relevant aerodynamics firstly requires information regarding all relevant wind field properties undisturbed by the OWT, which include wind shear, mean wind speeds and turbulences. Those wind field properties may be evaluated on the basis of measurements and/or calculated from different models or taken from common design standards, e.g. from IEC [1].

The three-dimensional wind field is mainly treated by stochastic approaches. However, deterministic approaches are still used to investigate turbine behaviour under certain operational conditions for calculations of extreme loads. The deterministic description of the wind field within state-of-the-art simulation codes allows for definition of horizontal and vertical wind components as well as of the wind shear, e.g. by using a logarithmic or exponential profile. Wind turbulence is generally represented in terms of discrete gusts (transients), e.g. with amplitude, rise time and directional shape as specified by design standards.

Stochastic approaches, based on probabilistic techniques, provide a more realistic model of the wind field than deterministic approaches. The temporal and spatial turbulence structure of the three-dimensional wind field is evaluated on the basis of spectral and coherence descriptions for example by using the Von Karman or Kaimal spectral models. Such stochastic approaches are used to evaluate fatigue loads and several extreme load situations like stand-still or idling. The latest draft of the third edition of the IEC 61400-1 standard introduces probabilistic load extrapolation techniques for the evaluation of extreme operating loads derived from stochastic simulations.

The rotor aerodynamics in all simulation codes mentioned below are based on blade element momentum (BEM) e.g. according to Glauert's theory [9, 10] and take into account certain corrections and extensions. Corrections and improvements of BEM-theory comprise: tip and root effects, turbulent wake state, 3D-effects and global and local dynamic effects, i.e. dynamic inflow and dynamic stall.

Application of more accurate CFD methods within integrated simulation codes still seems to be too expensive in computational terms even though computers today have significantly increased cpu-power. It can be assumed that, in the foreseeable future, CFD methods will remain reserved for detail and component calculations. More details on the treatment of aerodynamics within simulation codes are given in Molenaar [12] and Quarton [13]. Furthermore, Quarton gives an overview of design calculations in an evolutionary context.

2.4. Analysis methods

Three alternative methods are used within the simulation codes i.e. finite element (FE), multi-body-system (MBS) and modal approaches for the calculation of structural dynamics.

In the FE approach the wind turbine system is discretized into finite elements for flexural beams, lumped masses, springs and joints. In most cases the theory of linear elasticity but large deflections is applied. Solutions of the partial differential equations for the continua are approximated by the numerical solutions for the nodes. Usually this results in a fairly large number of degrees of freedom with the associated high computational effort. Compared to the modal approach FE formulations show fewer restrictions with regard to certain support structure geometries such as jackets and allow for modelling of material non-linearities which are relevant when dealing with non-linear pile-soil interaction problems. For more details on the application of FE-based approaches to aero-elastic simulations the reader is referred to the thesis of Ahlström [17], which however, has a focus on onshore wind turbines.

In the multi-body-system (MBS) approach the structure is approximated by a finite number of elements similar to the FE approach. These elements consist of rigid or sometimes flexural bodies, coupled by elastic joints. Such a discretized system is described with a finite number of ordinary or partially differential equations. Non-linear kinematics is treated more efficiently compared to the FE approach. MBS approaches have become more popular for applications in OWT modelling during the last years. MBS combines advantages from both, modal and FE since the set of equations of motion

remains relatively small and non-linearities may be considered. Furthermore, it allows for modelling of dynamics of mechanical systems with both large deformations as well as large rotations. In the modal approach the deflection of e.g. the rotor blades and the support structure is superimposed from a relatively low number of eigenmodes, which are extracted from a previous modal analysis of a simple FE model. The deflections of blades and tower are coupled with a low number of prescribed discrete degrees of freedom e.g. for rotor rotation, drive train flexibility, etc. The modal approach results in the lowest number of degrees of freedom (typically less than 30) and buys its high computational efficiency at the cost of a number of restrictions e.g. fixed number and type of degrees of freedom, assumption of linearity, etc. Due to the highly reduced number of degrees of freedom the modal approach proved to be very fast and adequate for simulations. Furthermore, according to Vugts [16] the pure and unmodified modal approach seems to be inadequate when dealing with jacket-type structures. Owing to the unfavourable convergence properties at superposition of the 3rd and 4th order derivatives of the displacement field, difficulties arise for the member force calculations of such structures.

3. Offshore Wind Turbine Simulation Codes

The first offshore wind farms in sheltered waters and based on relatively stiff foundations were designed prior to the availability of integrated simulation codes. Today a number of sophisticated codes exists for simulation of OWT in an integrated and/or superimposed manner. Most of them have recently been extended or are currently extended in order to meet the needs for OWT of the second generation. Obviously, measurement data will only be available after installation of such OWT. Therefore, detailed verification is complicated. Section 4.3 presents an overview of recent as well as current verification tasks and possibilities.
Selection of an adequate code for a certain design task requires knowledge of a range of code details, such as modelling capabilities and limitations, performed code verifications, implemented methods and underlying theories as well as additionally required codes and tools. For additional informations the reader is referred to Molenaar [12].

3.1. Status of current simulation codes

From the variety of aero-elastic simulation codes that are capable of simulating offshore wind turbines only the following are considered in more detail within this paper:

BLADED, version 3.67; Garrad Hassan and Partners Ltd. Initially implemented as an aero-elastic simulation code for performance and load calculations for onshore wind turbines, **Bladed** was extended to offshore applications for OWT with monopile or gravity-based foundations in 1999. Today, **Bladed** is a standard tool for simulation of OWT in the wind energy industry and is supplied with a sophisticated graphical user interface as well as post-processing tools. Extensions of **Bladed** in 2005 include the capability to model multiple member space-frame support structures and additional foundation models including suction caissons and a p-y representation of piled foundations. In addition, Bladed is capable of modelling tension-leg spar buoy designs of floating wind turbines.

FLEX5, DTU Copenhagen. Since version 5 the **Flex** code is able to simulate monopile and gravity base-founded OWT. As another industrial standard tool for simulation of OWT licensees are provided with the source code and allowed to adapt the code to their individual needs. The support structure is treated in a modular manner and divided into the tower and the combined sub-structure and foundation. Wave kinematics is generated externally by the pre-processing tool **Wavekin**, which is provided together with **FLEX5**.

HAWC2 (**H**orizontal **A**xis **W**ind **C**onverter); Risø National Laboratory. This successor version of the aero-elastic code **HAWC**, which is widely used and verified for research purposes, is being completely rewritten at Risø National Laboratory. As **HAWC** this code uses a FE-approach with Timoshenko-beam elements. Modelling capabilities of **HAWC2** cover OWT with bottom-mounted multiple member space-frame support structures as well as floating type concepts. In general, special support structures, such as floating or non-linear spring foundations, are modelled by a generalised user interface, which makes it possible for the user to interact with the structure through his own DLL. **HAWC** is currently used for verification of **HAWC2**, but **HAWC2** is intended to replace **HAWC**.

ADAMS/WT (**A**utomatic **D**ynamic **A**nalysis of **M**echanical **S**ystems - **W**ind **T**urbine), developed by Mechanical Dynamics, Inc. (MDI) under contract to the National Renewable Energy Laboratory (NREL). **ADAMS/WT** is a public domain toolkit designed as a pre-processor to create wind turbine models for the general-purpose, multi-body dynamics code **MSC.ADAMS**®. Modelling capabilities of **ADAMS/WT** cover OWT with support structures of the mono-tower and monopile type. Bottom-mounted multiple member space-frame as well as floating type concepts can also be used within **ADAMS**, but such support structures requires a definition by the user. Hydrodynamic and aerodynamic loads are calculated as for **FAST** (see below). Furthermore, the functionalities of the pre-processor **ADAMS/WT** are now available in **FAST**, denoted as **FAST-to-ADAMS** pre-processor.

TURBU Offshore, ECN. As a frequency domain tool **TURBU** allows for quick assessment of a number of sea states and therefore insight into the dynamic behaviour within early design phases. By the frequency approach it is possible to take into account the stochastic nature of environmental loads e.g. wind and waves in an efficient way. **TURBU** is intended for complementary use with time domain tools.

PHATAS IV (**P**rogram for **H**orizontal **A**xis wind **T**urbine **A**nalysis and **S**imulation); ECN. By incorporation of a more detailed tower model and consideration of wave loads **PHATAS** was extended to offshore applications. While finite elements are used for calculations of the RNA, the support structure is represented by its modal properties using the design tool **FOCUS5**. The support structures modelling capabilities covers mono-towers on monopiles with set of guy wires or a set of side-support bars

near the foundation. Furthermore, **PHATAS IV** allows for analyses of support structures of more arbitrary spatial topology by direct input of mass and stiffness matrices. Waves are generated either as stochastic waves with **ROWS** (**R**andom **O**cean **W**ave **S**imulator) or as deterministic waves with the **Streamfunction** code both from ECN.

ADCoS, AeroDynamic Consult GmbH (ADC). Intended for load simulation of onshore wind turbines using a FE approach. Modelling capabilities of ADC's in-house code **ADCoS** cover all kind of bottom-mounted multiple member space-frame support structures. Hydrodynamic loads are created by **WAVELOADS**, from the Fluid Mechanics Institute, University of Hannover.

FAST (**F**atigue, **A**erodynamics, **S**tructures, **T**urbulence) Version 6.01, NREL. In the current version **FAST** is predominantly intended to simulate OWT of the floating type. **FAST** provides a number of interfaces allowing for incorporation of externally evaluated loads and modal properties as well as for co-simulation with certain tools. Aerodynamic forces along the blades for example are generated by **AeroDyn** taking into account the aero-elastic behaviour of the wind turbine. Hydrodynamic load calculation differs from those presented for bottom mounted OWT in Section 2.3. Hydrodynamic effects and the describing forces which arises from arbitrary, time-varying motions of the floating type OWT are calculated on basis of the potential flow theory according to Cummins [21] and Ogilvie [22] using unit response functions and solution by convolution integral[2]. **FAST 6.0** uses SWIM from the Massachusetts Institute of Technology as a preprocessor to solve the frequency domain problem analytically for platforms of simple shapes such as surface piercing cylinders. Both, modal properties and hydrodynamic loads for support structures are required as user-input. The used support structure DOFs addresses to floating structures i.e. surge, sway, heave, roll, yaw and pitch allow to model support structures of the floating type as well as of the monopile type with (guyed) towers. Furthermore, the public domain code provides possibilities to create wind-turbine models for **MSC.ADAMS**®.

Other aero-elastic simulation codes for OWT such as the DUWECS code of Delft University [5] or the DHAT code of Germanischer Lloyd are not further discussed here, since they are used only as in-house codes. Table 3 presents an overview of some relevant details of the single codes with a focus on the capabilities and underlying models affecting the support structure and describing the offshore environment. It should be noted that descriptions concerning FLEX5 are restricted to the original version. Some licensees from the wind energy industry such as Vestas, GE Wind and RePower have already implemented notable modifications.

Table 3 Comparison of support structure and offshore environment modelling of current OWT simulation codes

Offshore environment	**Bladed**	**Flex5**	**HAWC2**	**FAST**	**ADAMS/WT & FAST-to-ADAMS**	**TURBU**	**PHATAS**	**ADCoS**
Deterministic waves	Airy^{+}, Stream	Airy^{+}, Stream	Airy^{+}	Airy	Airy	-	Airy^{+}, Stream	Airy, Stream, Stokes
Stochastic waves	PM, UD, JONSWAP & Airy^{+}, CNW	PM, UD, JONSWAP & Airy^{+}	PM, JONSWAP & Airy^{+}	PM, UD, JONSWAP & Airy	PM, UD, JONSWAP & Airy	UD &Airy	PM, UD, JONSWAP & Airy^{+} or 2nd-order wave theory	PM, UD, JONSWAP & Airy^{+}
Currents	sub-surface, near-surface, near shore	Sub-surface	Constant	-	-	Yes	Yes	-
Hydrodynamic load calculation	ME^{1,2,3}	ME^{1,2,3,4}	ME^{1,2,3}	*PFT*	*PFT*	ME^{1,2,3}	ME^{1,2,3}	ME^{1,2,3}
Structural modelling								
Analysis method	modal	modal	MBS	modal	MBS	MBS	modal -> SS FE-> RNA	FE
Integration method	Runge-Kutta 4th/5th order with variable time step	Runge-Kutta-Nyström	Newmark	Adams-Bashforth-Moulton method, 4th-order	MSC.ADAMS® provides different methods	time-domain application under construction	implicit iterative solution	Newmark
Tower & Sub-structure types	MT, MP, SF, GBS, FL	MT, MP	MT, MP, SF, GBS, FL	MPI *(MT, MP, GBS, FL)*	MT, MP, SF, GBS, FL	MT, MP	MT, MP, GBS, MPI(SF)	MT, MP, SF, GBS
Foundation types	MP,GBS,GP,SC	MT	MP, GBS, GP, UD	MPI *(MP, GBS)*	MP,GBS,GP	MP	MP, GBS	MP,GBS,GP
Foundation models	AF, DS^{1,2,3,4,6,7}	AF	AF, DS^{1,3,4,5,6,7}, UD	-	AF, DS^{1,2,3,4,7}	AF, DS^{1,2,3,5}	AF, DS^{1,2,4,5}	AF, DS^{1,2,3,4,5,7}

PM - Pierson-Moskowitz
UD - user defined
Airy^{+} - modification for free surface effects, e.g. Wheeler-stretching
CNW- Constrained NewWave
PFT – potential flow theory, taking into account diffraction and radiation

ME$^{1,..,n}$ - Morison equation for calculation of
1) relative kinematics
2) drag and inertia
3) added mass
4) slam
5) slap
6) breaking wave impact
7) MacCamy-Fuchs correction for diffraction

MBS *- multi-body-system*
FE *- finite elements*
SS *- support structure*
RNA *- rotor-nacelle assembly*
MT
FL *- mono-tower*
SF *- floating structures*
- arbitrary space frame structures, e.g. jackets

MP - monopile
GBS - gravity base structure
SC - suction caisson
GP - general pile *(axially and laterally loaded)*
MPI - user input of modal properties or system matrices

DS$^{1,..,n}$ - discrete springs
1) lateral (translational)
2) axial (translational)
3) rotational
4) distributed (Winkler-springs)
5) coupled
6) p-y and/or t-z-curves
7) non-linear
AF - apparent fixity length

[2] This requires the evaluation of frequency dependent added mass and damping coefficients of the floating type OWT and transformation to the time domain by Fast Fourier Transformation. By this approach diffraction effects are included in the wave excitation force. Build-in models for floating type configurations will be provided in version 6.1. Future versions of **FAST** will provide build-in models for bottom-mounted support structures using Morison equation for load calculation and different current models.

4. Development Needs

Current state-of-the-art simulation codes reached a high degree of sophistication and accuracy with respect to the design and simulation of OWT with monopiles and gravity-based foundations. However, certain development needs may be identified for both the design process and scientific models. Even more challenges and increased requirements with respect to simulation and design tools arise when dealing with OWT of the second generation. Furthermore, substantial verification of the simulation codes is a constant need.

4.1. Needs within the design process

Designing an OWT is an iterative process comprising a number of tasks. Not only integrated system models, but also sub-system models and component models are needed. However, this process can roughly be divided into two subsequent phases, the preliminary design and the detailed design.

Only a limited number of data regarding environmental conditions and the final design are available in the preliminary design phase. Within this phase insight into the design drivers and dynamics as well as a design concept based on the limited set of data are desired. This phase typically comprises parameter studies and design iterations on components and sub-systems e.g. blades, piles, the RNA or the support structure, but also on the whole system. Superimposing the results achieved from sub-systems models, leads to an approximative solution for the whole OWT. Iterative calculations on that basis allow for preliminary optimisation of the sub-systems and components, which are compiled to a concept of the OWT when entering the detailed design phase. Clearly, this concept contains uncertainties regarding calculated loads and responses. Furthermore, results of such calculations do not fulfill requirements for certification, but offer a very good basis for detailed design optimisations of both the whole OWT and single components.

Finding an optimised and economic design requires a sophisticated methodology with appropriate tools for each design task. One important type of tools certainly are aero-elastic simulation codes using integrated system models for load calculations. A number of such codes is presented in section 3.1. Detailed calculations and results of such codes are needed for final design optimisations in the detailed design phase as well as for certification.
Only a limited number of tools for preliminary optimisation of support structures for OWT such as MonOpt[3] exist. It is common practise in the design of OWT with monopiles, that integrated simulation codes are used even in the preliminary design phase as indicated in Figure 7. Clearly, this still is an appropriate approach when dealing with a low number of design parameters. However, current state-of-the-art simulation codes are predominantly intended for load and performance calculations that are needed for certification and show only limited capabilities in the optimisation of support structures for OWT of the second generation. To meet future design tasks associated with the significantly increased number of design parameters of such OWT, designers need support from more differentiated tools focusing on each single design task. This requires either development of additional tools focusing on design optimisation of support structures with a crude, but adequate representation of the RNA or extensions of existing simulation codes. In this context it might be useful to distinguish between design tools, i.e. fast and approximative tools with sophisticated design capabilities, and simulation tools, i.e. tools for accurate simulation of loads and performance, which may be provided within a single code.

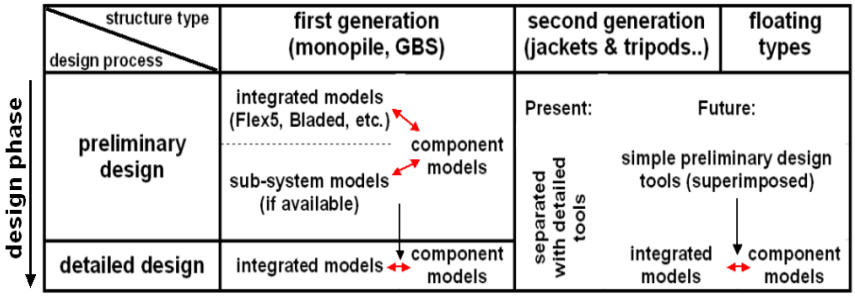

Figure 7: Requirements of the design process

4.2. Scientific needs

All kinds of components, sub-system and integrated system models as well as models used to describe environmental influences and interactions are mathematical representations of physical processes and properties. Clearly, the accuracy of the simulations depends on the quality of input values as well as accuracy and limitations of the used models. A large number of different models and methods is necessary to simulate an OWT and it would be far beyond the scope of this paper to

[3] Preliminary design and optimisation tool for onshore und offshore support structures (mono-tower on monopile)

discuss all of them with respect to their applicability and potentials for further improvement. Furthermore, model requirements within the designer community differ in some aspects from those of the scientific community. However, a consensus is necessary enabling both communities to develop and adapt complementary models.

Regarding the support structure, the soil-pile interaction model for piled foundations is probably one of the most critical aspects. The non-linear p-y-approach with a proper linearization still provides good results for monopiles with a diameter of up to 6 m under static loading. Results for cyclically loaded monopiles on the other hand are highly questionable since the semi-empirical p-y-method is based on field tests on piles with diameters in the range of 0.5 m, neglecting the non-linear influence of the pile diameter. This problem becomes even more serious when dealing with transient loads, which are typical for OWT. Currently, very detailed FEM-based models are developed taking into account hypo-plastic relation for granular materials within the constitutive equations, with additional consideration of hysteretic and accumulation effects . As long as no simplified models of comparable accuracies are available such detailed models may be used as component models for the detailed design of the pile. However, such models might possibly also be used in preliminary design phase in order to derive simplified soil-pile interaction representations for further design calculations.
Furthermore, the soil-pile interaction, and therefore the dynamic properties of the whole OWT, is significantly influenced by the effect of scouring. Current design practice still uses either constructive design features for permanent or dynamic scour protection or conservative assumptions such as an assumed scour depth of e.g. 2.5 pile diameters if no other data are available as proposed by GL [2]. Although, especially the sea-bed in larger depths below the sea floor participates in load transfer between pile and soil, this rough assumption may lead to significantly changed dynamic properties and load transfer mechanisms and therefore to under-predicted or over-predicted fatigue loads. According to IEC [1] such other data may be obtained on the basis of previous records from sites with similar sea floor characteristics, from model tests or from calculations calibrated by prototype or model tests.
Integrated models simultaneously consider wind and waves. As shown in Figure 1 certain interactions exist between air and sea. Both the combined wind and wave loading as well as short-term and long-term correlations of wind and wave loading have a significant impact on the simulated loads. As mentioned before, Kühn [5] showed that the aerodynamic damping of simultaneous wind and wave loading during power production leads to reduced loads compared with superimposed loads from isolated calculations. Furthermore, assumed correlations of wind and waves in space and time also have a major influence on calculated loads, so that misalignment between wind and wave direction may significantly influence the magnitudes of dynamic responses in lateral direction owing to reduced effective aerodynamic damping. Therefore, better met-ocean data and especially data bases are needed for the design process of OWT to exploit further optimisation potentials. This requires proper incorporation and/or adoption of current modelling possibilities, e.g. within hind cast based systems, into practical models for design purposes of OWT as well as further improvements on current models.
A certain robustness of the OWT design against changed conditions and long-term variation in dynamic properties is necessary. Furthermore, this requirement also contributes to the uncertainties of the models mentioned and all other models and methods used during the design process. A proper design robustness can only be achieved on the basis of an adequate design methodology, a sophisticated design process and sufficient experience of the designer.

4.3. Code verification

Verification of the codes is a continuous task associated with code development. Several code verification projects for aero-elastic design codes for onshore wind turbines, such as the EU-JOULE project 'Verification of European Wind Turbine Design Codes', have been performed during the last years. Due to recent extensions of the support structure models within the codes, further major verification such as performed within the OWTES project [18] is needed for the offshore case. However, a large-scale verification of the codes is a time-consuming and expensive task. Therefore, code verification is restricted to a certain range of conditions and designs. Currently the verification project **O**ffshore **C**ode **C**omparison **C**ollaboration[4] is being carried out, involving an international group of experts and most of the aforementioned codes. This project will last approx. four years and it will provide a systematic comparison of all critical elements of the codes focusing on the support structures and offshore loads. The OC^3 ode verification comprises a step-by-step approach starting with verification of single, uncoupled elements of the codes, such as the support structure and wave loads. Subsequently, the degree of complexity and couplings will be increased. Finally, the fully integrated models of the OWT should be compared. The intended step-by-step approach allows to determine sources of differences and therefore to improve the codes during the project.

[4] **OC^3** is part of Subtask 2-Technical Research for Deeper Water within Annex XXIII of the **I**nternational **E**nergy **A**gency

Code verification is possible on the basis of both code-to-code comparisons and code-to-measurement comparisons. The best solution would involve both approaches. Difficulties occur through lack of appropriate measurement data, since no OWT with support structures of the second generation have actually been installed. In addition, classification of relevant data may limit code-to-measurement comparison. Therefore the question arises, whether verification of the fully-integrated system models of the codes is possible or whether it is limited to single components and sub-systems when dealing with OWT of the second generation. On the other hand measurement data for OWT with monopile foundations exist and verification of integrated models for such structures within the codes is possible and has already been performed e.g. within OWEMES [18]. Taking into account the availability of measurement data for OWT with support structures of the first generation and the lack of such data for second-generation OWT the answer to the first question as to the possibilities of verification depends on the following question: How does the TYPE of support structure affect the ADDITIONAL interactions (qualitative, not quantitative!) of fully-integrated system models COMPARED to separated system models? Consider aerodynamic damping for example. Clearly, the order and magnitude of aerodynamic damping strongly depends on the dynamic properties of the support structure, but the type of support structure has a neglecting influence on THE NATURE OF this physical effect. And it can be stated, that additional interactions of fully-integrated system models compared to both separated system models for the wind turbine as well as for the offshore structure are influenced by the type of support structure in a neglecting manner. Verification of the implemented models and routines for those additional interactions by measurements on OWT, e.g. with monopile support structures, may therefore be considered as a verification of those interactions for all types of support structures. On this basis a verification of the codes for OWT of the second generation is possible despite the lack of measurement data.

5. Conclusions

In the future, OWT will also be built in deeper water. Besides the established support structure concepts, i.e. monopiles and gravity-based structures, a second generation of bottom-mounted braced support structures is deployed from a certain water depth on. Such support structure types of the second generation show a significant increase in the number of design parameters compared to those of the first generation. Most of the current state-of-the-art integrated simulation codes have recently been extended with a focus on the modelling needs for support structures of the second generation. However, the variety of support structure concepts increased significantly with the second generation and not all types of support structures and relevant loads can be modelled in each simulation code. Therefore, a number of simulation codes with integrated system models is presented within this paper focusing on the support structure and offshore environmental modelling capabilities. An adequate code must be chosen dependent on the actual design task. Within the design process of OWT of the second generation those integrated simulation codes are predominantly suited for detailed calculations in the final design phase as well as for certification. In the preliminary design phase, on the other hand, fast and approximative calculations are required. Although optimisation of the sub-systems in this phase strongly depends on the experience of the designer it is important that adequate assistance is provided by tools that help to handle and optimize the large number of design parameters.
A differentiation of the tools which are needed within the design process may result in design tools and simulation tools. Design tools provide very specialized modelling capabilities for single sub-systems and components, but are limited regarding their simulation capabilities. Simulation tools on the other hand allow for accurate simulation of the whole OWT with respect to load and performance calculation, but are limited regarding their design and optimisation capabilities. Clearly, both types of tools are required and may even be provided by a single code. The current lack of proper design tools for support structures of the second generation either requires extensions of the existing simulation codes or implementation of additional tools.

Recent extensions of current simulation codes related to the modelling needs of the second generation OWT require proper verification. The Offshore Code Comparison Collaboration project as part of IEA Annex XXIII addresses this need. Although no OWT of the second generation have been installed yet and therefore no measurement data are available, verification of the codes is possible when using a proper strategy and range of conditions and designs.

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